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NASA Unmanned Flight Anomaly Report:

INVESTIGATION OF MECHANICAL ANOMALIES AFFECTING INTERPLANETARY SPACECRAFT

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FOREWORD

This document was prepared by the Reliability Engineering Section of the Jet Propulsion Laboratory's Office of Engineering and Mission Assurance (OEMA) to describe recent results and progress of a Flight Anomaly Characterization (FAC) research task. It represents one of a series of analyses of in-flight hardware anomalies which have occurred on Jet Propulsion Laboratory (JPL), Goddard Space Flight Center (GSFC), and U.S. Air Force unmanned space programs. Funded by NASA Code QT under Research Technology Operation Plan (RTOP) 623-63-03, entitled *Flight Anomaly Characterization*, their objective is to search for meaningful characterizations of in-flight anomaly data relating to trends, patterns, or similarities that can be exploited to improve product assurance programs. Such improvements may ultimately lead to reduced numbers of anomalies on future unmanned flight programs.

For further information on the content of this report, contact David Oberhettinger at (818) 542-6960.

ABSTRACT

This NASA Unmanned Flight Anomaly Report analyzes reported anomalies related to the in-flight performance of mechanisms on Jet Propulsion Laboratory (JPL) unmanned space programs. With hardware design as the most common probable cause, these anomalies relate to positioning of the entire spacecraft, such as gyro anomalies; structures, such as physical shadowing of the solar array; and modules or components, such as antennas. This type of anomaly tends to pose an major mission risk and is particularly suited to prevention through modeling during design and test. The objective of the analysis was to:

1. Determine whether the anomalies were isolated incidents or whether the failure modes represent a risk to future unmanned missions.

2. Identify product assurance process improvements to reduce mission risk.

The report identifies a pattern of hardware anomalies due to mechanical faults. The impact of these failures on the respective missions was significant in most cases. The report recommends enhanced inheritance reviews for complex mechanisms, additional design analysis and review, and JPL organizational changes. Additional ground testing is not viewed as beneficial in preventing these mechanical problems.

REFERENCE: (1) *Development of a Method for Flight Anomaly Characterization*, JPL document D-11382, dated January 1994.

I. INTRODUCTION

Scope

This NASA Unmanned Flight Anomaly Report presents the findings of an analysis of anomalies involving spacecraft mechanisms which did not function in spaceflight as intended. The investigation is limited to the JPL Viking, Voyager, Magellan, and Galileo missions as documented in the JPL Payload Flight Anomaly Database (PFAD). Maintained by the JPL Reliability Engineering Section, this database presently includes over 5000 in-flight anomaly reports.

The PFAD reports include anomalies reported by Goddard Space Flight Center (GSFC) and the U.S. Air Force. With the exception of gyro anomalies, however, these agencies' flight programs were not analyzed in this report due to the lack of detailed information on mechanical actuation anomalies. Major JPL flight programs prior to Viking were excluded from study because of the degree of hardware obsolescence-- conclusions drawn from the flight behavior of early 1960s era hardware are not clearly applicable to current and future flight hardware reliability programs.

This report is one product of the Flight Anomaly Characterization (FAC) study, funded under NASA RTOP 323-63-02. The methodology established in Reference (1) was applied to the analysis of hardware positioning anomalies.

Purpose

This study is one of a series of Unmanned Flight Anomaly Reports funded by NASA Code QT to document investigations of in-flight spacecraft and instrument anomaly data. The results are principally directed toward recommending product assurance process improvements which would lead to a reduced level of risk for future unmanned space missions. The conclusions from these studies are pertinent to the NASA Small Spacecraft Technology Initiative, which proposes a higher risk approach to flight hardware design.

Method

Reference (1) suggests a two-step methodology for grouping and analyzing sets of in-flight spacecraft anomalies with common characteristics, allowing identification of product assurance implications for future programs. In that document, a flow diagram was prepared showing pertinent data from each in-flight anomaly report in the PFAD. To date, this diagram has been prepared only for the major JPL spacecraft due to the large number of GSFC and USAF programs. After the anomalies were arranged by spacecraft and subassembly, those that appeared related were designated as a group for further analysis. A second flow diagram (see Figure 1) is prepared for each candidate grouping of anomalies with possible product assurance program significance; failures of complex mechanisms was identified as one of these groupings. This second diagram is further analyzed to validate the suspected correlations (identified by "cross-links" in Figure 1), and to identify any product assurance program implications.

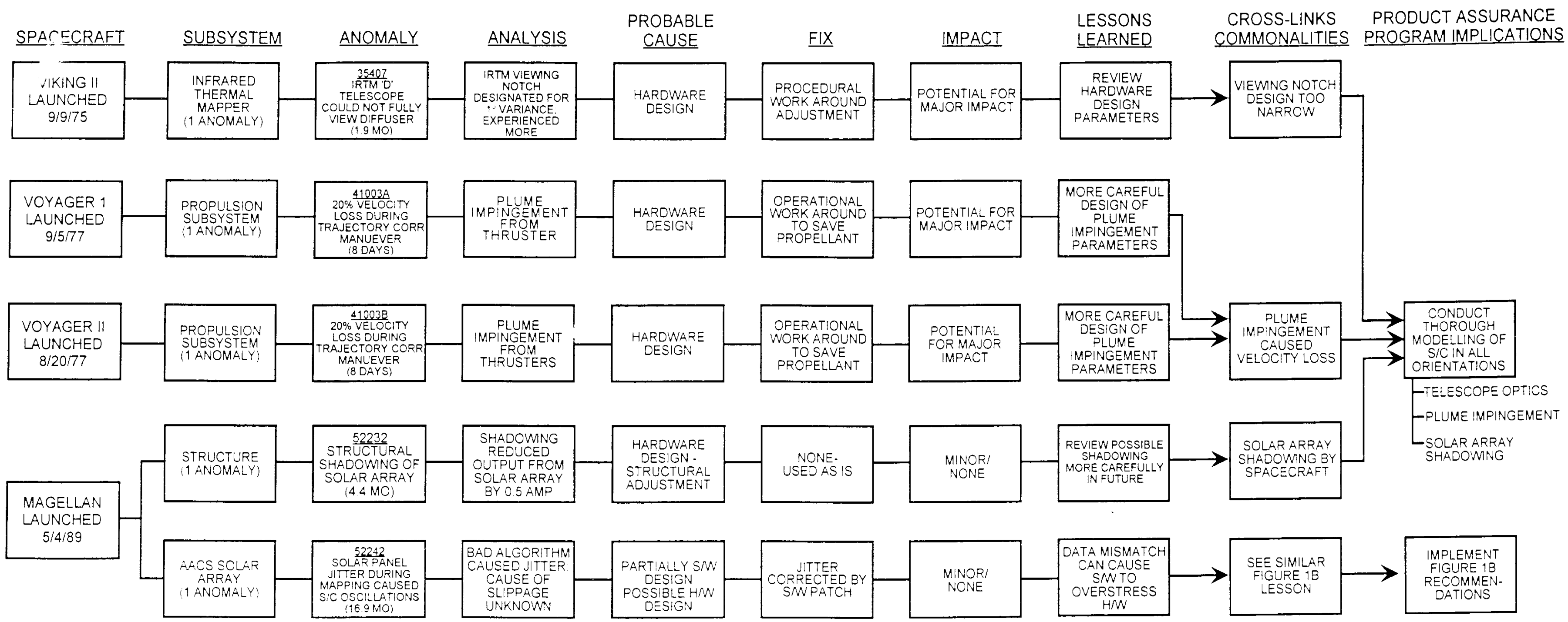
II. DATA ANALYSIS

JPL Programs

Applying the flow diagram technique to major JPL spacecraft programs, one characteristic pattern that emerged was a number of early to mid-mission anomalies revealing mechanical flaws or structural incompatibilities. These are notable in that they include major assemblies and structures which typically undergo extensive functional test prior to flight. A third sub-category is anomalous in-flight performance of inertial reference units (IRUs), included in this category because of the mechanical complexity of spinning bearing gyros.

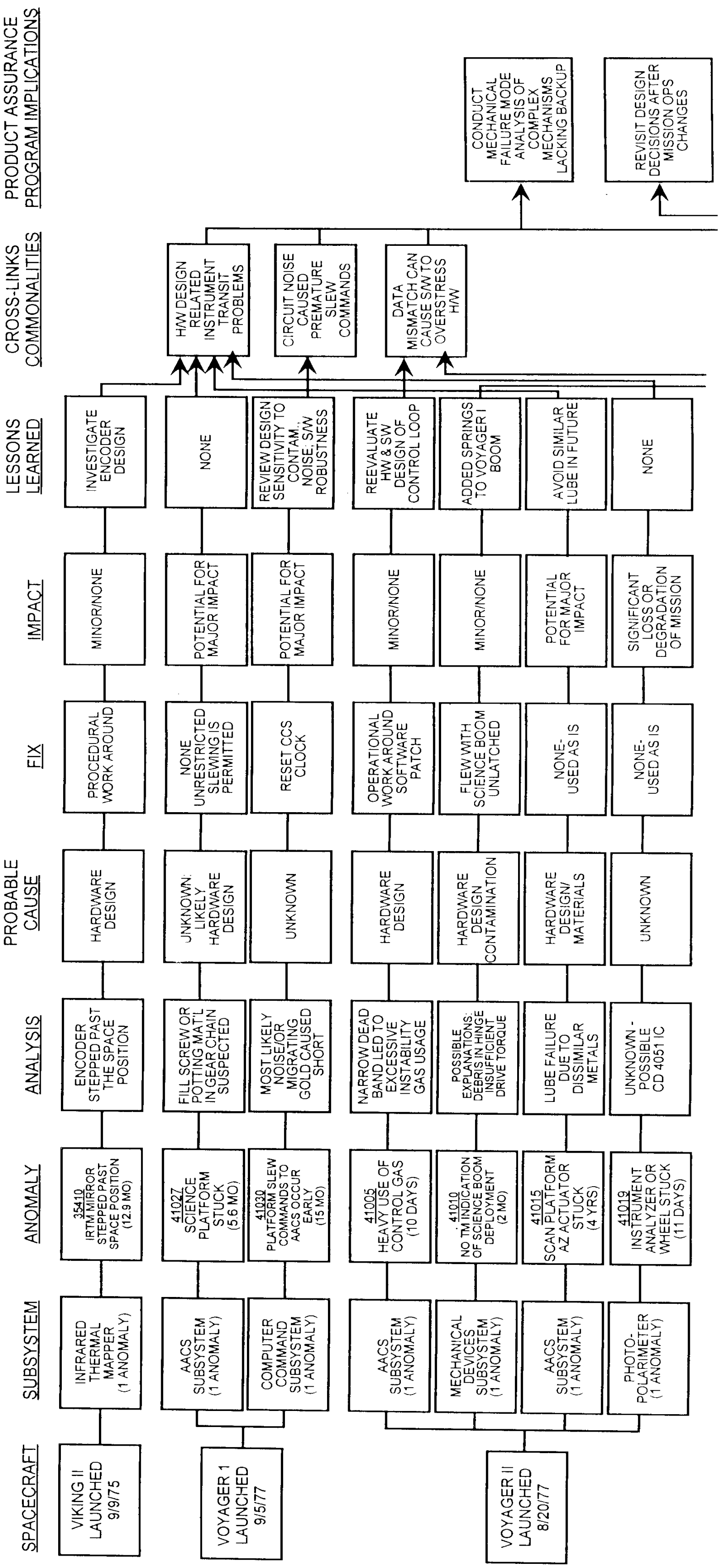
In-flight anomalies of JPL instruments aboard non-JPL spacecraft were not included in this analysis because of the great variation in the extent of JPL (or even NASA) Reliability Engineering cognizance over instrument design. The JPL failures are examined in Figure 1 using the flight anomaly characterization methodology demonstrated in Reference (1). Twenty-two in-flight anomalies, including 12 rated as "Major Loss or Mission Degradation," "Potential for Major Impact," or Significant Loss or Degradation of Mission, were documented on the Viking, Voyager, Magellan,

FIGURE 1a

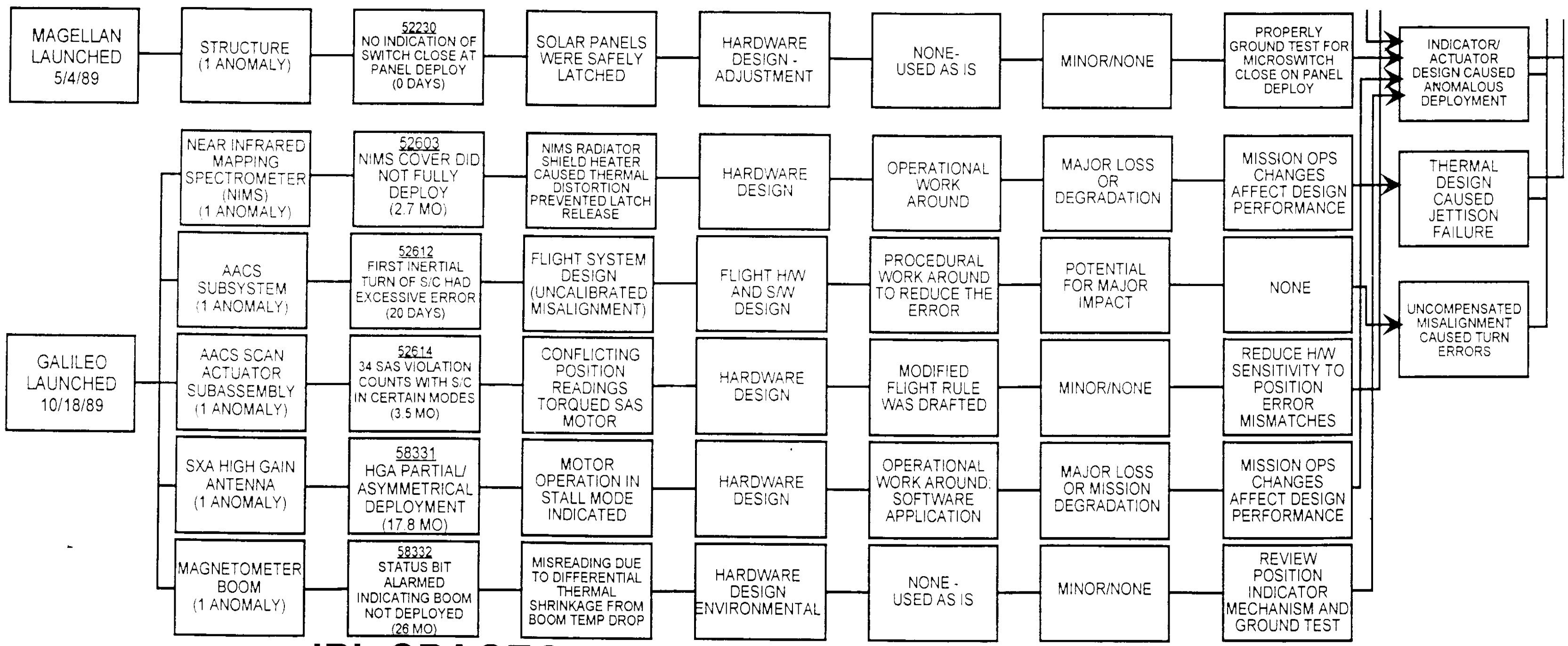


JPL SPACECRAFT - STRUCTURAL INTERFERENCE ANOMALIES

FIGURE 1b

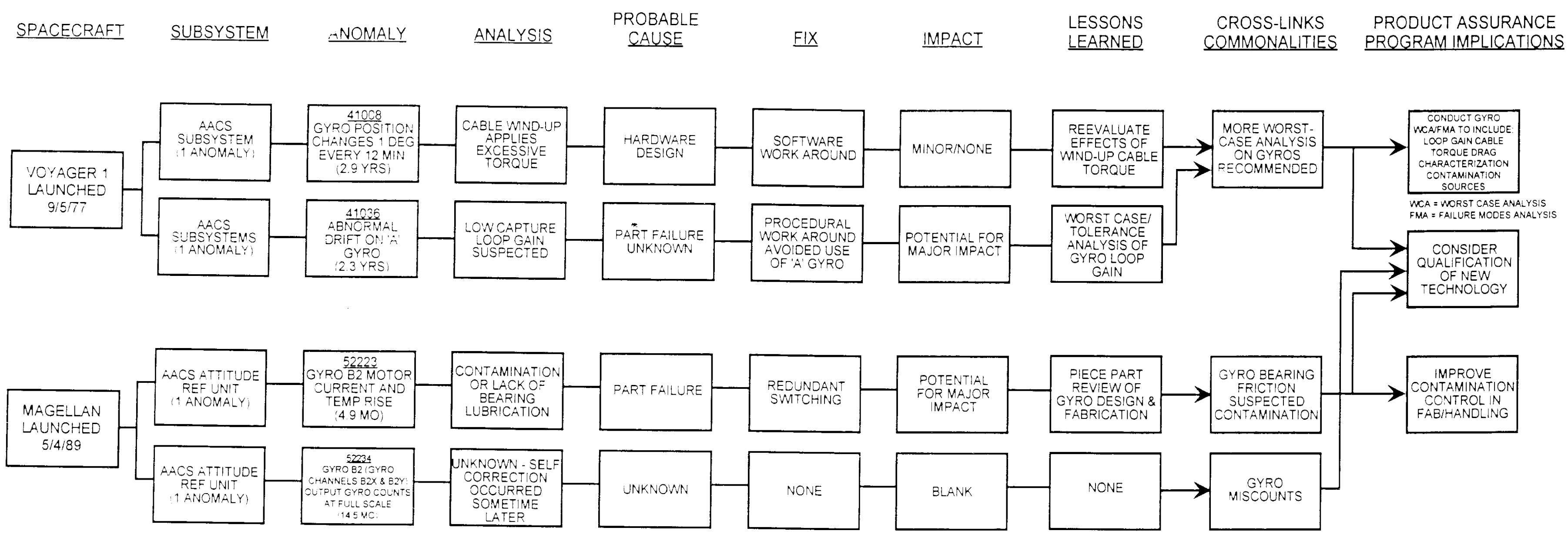


The bottom of Figure 1b is continued on the next page.



JPL SPACECRAFT - MECHANICAL ACTUATION ANOMALIES

FIGURE 1c



JPL SPACECRAFT - GYRO ANOMALIES

and Galileo flight programs. The trend does not appear specific to any particular flight program; the Attitude and Articulation Control System and instruments are the most common subsystems affected. Most of the non-IRU failures occurred when the affected mechanism was first exercised, revealing a functional design defect or incompatibility which had not been recognized by designers.

Table 1 shows that this pattern of anomalies occurred mostly in non-redundant hardware. Moreover, a high risk to the mission (represented by Mission Impact ratings in bold face type) had a strong correlation with lack of redundancy. Although software patches or operational workaround solutions were sometimes feasible, this pattern of anomalies has posed a substantial threat to mission success.

Hardware design emerges in Figure 1 as the major culprit among the probable causes of the anomalies. However, the anomalies in this structural/mechanical/IRU grouping are too disparate for fruitful analysis of common failure modes. Rather than revealing distinct failure trends, the data analysis in the remainder of Section II is directed at eliciting patterns of design flaws which suggest possible oversights or vulnerabilities in the design assurance process.

Structural Interference

The anomaly characterizations in Table 1 include the following incidents documented by in-flight Problem/Failure Reports (PFRs) where the structure of the spacecraft or instrument interfered with mission operations:

PFR 35407. The Infrared Thermal Mapper (IRTM) aboard the Viking Orbiter was designed to scan the surface of Mars for signs of warmth. After ejecting the bioshield installed to prevent contamination of Mars with Earth organisms at 1400 mission hours, a problem was discovered with alignment of the IRTM and its housing. The scan range of the IRTM scan platform envelope did not permit the "D" telescope to fully view the diffuser plate. It was determined that the design of the platform alignment shim caused the IRTM misalignment. Specifically, the shimming and positioning of the cam to give the proper cone and clock constraints relative to the bus and solar panels resulted in the IRTM viewing notch moving more than the 1^0 tolerated by the design.

The mission impact was evaluated as "Potential for Major Impact," there was no redundant capability, and no operational workaround was feasible. The resolution was "Use as is."

Anomaly Cause: Incompatible tolerances (hardware design producibility

PFR 41003 A&B. A more definitive example of structural interference was the Voyager I and II plume impingement. Eight days after launch of Voyager I, doppler measurements determined that the observed ΔV was approximately 20 percent less that the predicted ΔV. This performance loss was verified by tracking data for both Voyager spacecraft during trajectory correction maneuvers (TCMs). Since both spacecraft exhibited nearly identical losses and propulsion telemetry indicated nominal thruster operation, hardware malfunction was eliminated as a factor.

The preflight predictions for ΔV had been based on a simple analysis which forecast a minor velocity loss due to spacecraft struts impinging on the flow field of the thruster plume. Repeating this analysis using more sophisticated techniques, the anomaly investigators obtained much higher plume impingement losses. Since the results of the revised analysis closely approximated the observed loss, the anomaly was attributed to plume impingement.

Table 1 - JPL Spacecraft Hardware "Positioning" Anomalies

Subsystem Affected	Mission Impact[1]	Redundant Capability
VIK II - Infrared Thermal Mapper Viewing Notch	**Major**	No
VIK II - Infrared Thermal Mapper Mirror	Minor	No
VOY I - Thruster Plume Impingement	**Major**	No
VOY I - Stuck Science Platform	**Major**	No
VOY I - Anomalous Platform Slew Commands	**Major**	No
VOY I - Excessive Scan Platform Cable Torque	Minor	Yes
VOY I - IRU Drift	**Major**	Yes
VOY II - Weak Science Boom Deployment Drive	Minor	No
VOY II - Thruster Plume Impingement	**Major**	No
VOY II - Stuck Scan Platform	**Major**	No
VOY II - Excessive Control Gas Usage	Minor	No
VOY II - Stuck Instrument Analyzer Wheel	**Significant**	No
MGN - Shadowed Solar Array	Minor	Yes
MGN - Panel Deployment Switch Defect	Minor	No
MGN - Solar Panel Jitter	Minor	No
MGN - IRU Output at Full Scale	Blank	Yes
MGN - Gyro Motor Current and Temp. Rise	**Major**	Yes
GLL - Stuck Latch on NIMS Cover	**Loss**	No
GLL - Magnetometer Boom Deployment Anomaly	Minor	No
GLL - Flight Guidance System Misalignment	**Major**	No
GLL - High Gain Antenna Deployment Failure	**Loss**	No
GLL - Scan Actuator Errors	Minor	No

[1] *Loss* = Major Loss or Degradation, *Major* = Potential for Major Impact,
Significant = Significant Loss or Degradation of Mission, *Minor* = Minor/None

This situation was not amenable to operational workaround because the pitch and yaw thrusters were affected unequally. The only feasible corrective action was to redesign the mission profile to conserve propellant. The mission impact was evaluated as having "Potential for Major Impact."

Anomaly Cause: Insufficient analysis of structural interference (hardware functional misapplication

PFR 41005. A very heavy duty cycle of the attitude control thrusters caused Voyager II to experience heavy use of attitude control gas during deployment of the NIMS cover (see PFR 52603). During a pitch turn, plume impingement from the pitch thrusters (see PFR 41003B) caused a low actual thrust, leading to a large pitch overshoot at the start of the turn. This resulted in a technical "angle limit violation" which forced spacecraft corrective measures leading to heavy gas duty cycles in all three axes. The problem condition was aborted after an hour, and an AACS software patch prevented a reoccurrence.

Anomaly Cause: Hardware Design

PFR 52232. A 0.5 amp deviation in the +X solar panel output, as compared to the -X panel output, was detected 4.4 months after launch of Magellan. The timing of the power loss was coincidental with a penumbral spacecraft alignment placing the altimeter antenna (ALTA) structure in front of the solar panel in line with the sun. Data suggested that the ALTA was casting a shadow onto the lower portion of the +X panel, reducing power generation. Review of pre-launch photos and drawings showed such an overlap. Due to an adequate power margin, the loss of 0.5 amps when the ALTA was in front of the solar panel was viewed as minor and as having no mission impact.

Anomaly Cause: Insufficient analysis of structural interference (structural design

PFR 52242. The Magellan solar panels jittered during mapping passes, causing the spacecraft to oscillate. Analysts noted a growing divergence since the beginning of mapping operations between the solar array drive motor (SADM) commanded position and the potentiometer reading of actual position. If this slippage had been allowed to continue, flight software would eventually have signalled a SADM Control Loss fault indication. JPL attributed the slippage to torque applied to the drive mechanism by the repeated changes in the direction of panel movement during jitter. The jittering effect itself, however, was caused by a deficiency in the flight software algorithm used to calculate the desired panel position for oblique sun incidence angles. This problem was corrected with a patch to the articulation control flight software, and the jitter was eliminated.

The solar panel design is susceptible to slippage, which may increase with frequent commanded panel movement, such as during panel unwinds. The uncommanded movement from the jitter exacerbated this manageable condition. Without the jitter, occasional recalibrations to correct divergent readings may still be necessary to preserve SADM fault protection.

Anomaly Cause: Principally Software Design, With Hardware Design Elements

<u>Mechanism Actuation</u>

Thirteen mechanical actuation anomalies spanning all the major JPL spaceflight programs were reported, as follows:

PFR 35410. When operating in normal mode, the Infrared Thermal Mapper (IRTM) scan mirror aboard the Viking Orbiter should have stepped from planet position to space position every 72 seconds, and then remained in the space position for 3.36 seconds. On twelve occasions in 1976, the mirror stepped past the space position without stopping and continued to the reference position.

Two anomaly modes were identified by analysis. First, during mirror transit from planet position to space position, the mirror position encoder occasionally lost the space "TRUE" signal, causing anomalous mirror stepping sequences and DC-RESTORES. This problem was resolved by a software upgrade inhibiting DC-RESTORES when the mirror was not in the space position.

Second, an extra mirror position step sometimes occurred in space-to-planet transition, so that the IRTM pointed slightly past the nominal planet pointing position. These modes were likely caused by a combination of normal wear in the motor gear drive chain for the mirror, and misalignment of the mirror drive with the encoder. The occasional offset pointing problem could usually be corrected by commanding the IRTM mirror to the space position and then back to the planet position.

Anomaly Cause: Hardware Design

PFR 41027. On Day 54 the Voyager I science platform stuck during an azimuth slew. After lab and in-flight tests were performed, platform motion was successfully commanded, and the anomaly did not recur. The spacecraft anomaly team (SCAT) investigating the incident were concerned that the same actuator design was to be used to articulate booms on Galileo.

Test results supported possible contamination of the scan actuator gear train with potting material, or actuator clutch slippage. Since Voyager performance was not significantly affected, no further action was taken, although test and evaluation of the actuator clutch by the Galileo project was recommended.

Anomaly Cause: Possible Hardware Design or Gear Contamination

PFR 41030. At 15 months into the Voyager I mission, it was discovered that the Command and Control System (CCS) was sending premature slew commands to the Attitude and Articulation Control Subsystem (AACS). Further analysis showed that all events generated by processor A in the CCS were occurring 48 seconds early. Sequence timing in the CCS is based on a clock driven by the 2.4 Khz power frequency. It is believed that extra counts picked up by the CCS ripple-counter, possibly due to circuit noise or IC particle contamination, placed the CCS timing out of phase with the Inertial Sensor Subassembly (ISS). This caused the CCS clock to be reset, creating a 48 second offset. The corrective action was to reset the clock to eliminate the offset and to revise command software to provide for an offset test.

Anomaly Cause: Unknown

PFR 41010. When the Voyager II science boom was deployed during launch, mission control failed to receive the full deployment indication. It was concluded that the boom deployed to within 0.2 degrees of latching, but it did not latch. No specific failure cause could be identified; JPL concluded that the likely cause was either debris in the folding strut hinge, or insufficient driving torque in the folding strut delivered in the position just prior to full deployment. Additional springs were added to the science boom deployment mechanism on Voyager I, and boom deployment was successful on this spacecraft.

Anomaly Cause: Unknown

PFR 41015. The Voyager scan platform's azimuth actuator stuck at 260° azimuth and 20° elevation. The anomaly appeared to have been caused by an actuator lubricant failure: corrosion from dissimilar metals in the actuator gears and gear shafts and water in the lubricant. This corrosion was worn away during actuator use; the debris jammed the gear/shaft bearing assembly.

The actuator was freed by permitting the actuator gears to cool. After testing the mechanism at various slew rates, scan platform slewing was restricted to a low rate. Although mission objectives were met, an opportunity to view Saturn and its rings at high phase angles was lost, and images of Tethis were missed.

Anomaly Cause: Hardware Design

PFR 41019. The Photo Polarimeter instrument analyzer wheel on Voyager stuck in Position 2 and would not move. Powering the instrument on and off caused no change. One explanation of the failure was a failed integrated circuit in the motor step logic. No corrective action was feasible, and some loss of data quality and quantity resulted.

Anomaly Cause: Unknown

PFR 52230. Following release of the two solar panels during near-Earth launch phase, Magellan telemetry provided no initial indication that the panels were latched. The microswitch on each panel must close to provide a latch indication. The panels were then rotated into a position where they received a "gravity assist" at the next burn. A solar panel latch indication was received a few seconds after engine ignition, so no further action was required.

Analysis of launch engineering telemetry showed that the solar panel latch indicator changed to a "LATCHED" indication eight seconds after receiving the assist, and the mission impact of this anomaly was rated as "Minor/None." Although the anomaly may represent a failed indicator, the prevailing view at JPL is that the solar panel deployment mechanism failed to fully deploy the panels per design.

Anomaly Cause: Hardware Design

PFR 52603. The instrument optics cover and radiative cooler cover were commanded to be jettisoned from the Galileo Near Infrared Mapping Spectrometer (NIMS). The two covers were designed to be unlatched simultaneously by a pair of lanyards operated by a pyro-actuated release mechanism. The subsequent absence of the expected cooling trend for the Focal Plane Assembly (FPA) was interpreted as a failure of the cooler cover to fully eject. After de-energizing the NIMS cooler shield heater, the FPA temperature plunged, and it continued to drop at the nominal rate after the shield heater was re-energized.

Failure investigation concluded that excessive heating of the cooler shield by the shield heater caused thermal distortion of the cover and shield, preloading the spring-driven latch pin and preventing cover release. Energizing the 30 watt shield heater prior to cover ejection was an add-on flight sequence to drive contaminants from the radiator shield. This concern about contamination arose years after the hardware had been qualified. The shield heater was never activated during cover deployment thermal/vacuum tests, and hardware designers were not informed of the change in planned sequence. Hence, design and qualification of the hardware were based on faulty assumptions.

Anomaly Cause: Operational Procedure

PFR 58332. A microswitch on the Galileo Magnetometer Boom sends a signal when the boom, which is collapsible, becomes fully deployed. About two years into the Galileo mission, the signal changed to an indication that the boom was not deployed. However, all other spacecraft indications suggested that the boom was deployed.

Attached to the Mag Boom is a beryllium-copper deployment lanyard, which is fed out by a rate limiter to control the speed of boom self-erection during deployment. Normally slack after deployment, thermal shrinkage of the lanyard is believed to have rotated the microswitch bracket about its mounting screws. Ground tests confirmed that lanyard shrinkage (caused by a drop in the temperature of the fiberglass boom structure) would un-actuate the switch and change the telemetry state.

Anomaly Cause: Hardware Design

PFR 52612. When the first inertial turn maneuver of the Galileo spacecraft was commanded, an excessive turn error resulted. The 9 degree turn stopped about 1 degree short of the desired, attitude. A turn undershoot was not considered of real concern, and error correction could await minical (a coarse calibration based on a limited number of data points). However, more significant attitude errors plus erroneous trips of thruster fault protection were anticipated with larger turn radii, and instrument damage could result during turns made after cover deployment.

Analysis showed that the turn itself was extremely accurate and that the error was introduced during the 175 degree stator slew that preceded the turn. The error built up during this near-maximum slew caused flight software to believe that the turn had started in the wrong place, and flight software performed an "accurate" turn to what it thought was the correct attitude. Hence, the spacecraft turn accuracy error budgets did not reflect the effect of stator-to-platform misalignment on the gyro-based attitude estimate.

To minimize turn errors, real-time stator prepositioning commands were sent before each turn. A minical reduced the residual error to acceptable levels, and the full Scan Calibration Program Set (SCALPS) calibration procedure provided further error reductions.

Anomaly Cause: Hardware and Software Design

PFR 52614. Following Galileo star sightings, the Scan Actuator Subassembly (SAS) controller erroneously commanded full-scale torque of the SAS. Occurring during celestial pointing operations, about 87,000 of these violation counts were generated during the Venus flyby, corresponding to 87,000 individual applications of full-scale torque to the SAS. This jerky motion raised concern about accumulated bearing wear in the SAS, and also about scan platform pointing performance.

The anomalies were charged to uncompensated star scanner misalignment (see PFR 52612). At instances of star sightings, a significant mismatch arose between the gyro propagated position errors and star based position errors. Software interpreted this discrepancy as a real-time increase in bearing friction, resulting in a demand for additional torque from the SAS motor to compensate for the friction.

To lessen the risk of bearing wear, a workaround was ordered to slew the SAS once each day during flyby science-pointing to redistribute bearing lubricant. Also, a software command was provided to disable science-pointing scans during extended periods of the flyby when scan platform science was not active. The standard corrective action to minimize accumulated position error mismatches is commanding in-flight calibration. However, since low telemetry rates prevent measurement of SCALPS calibration procedure effectiveness in reducing the SAS torque spikes, an SAS controller code change was also added to AACS software.

Anomaly Cause: Hardware and Software Design

PFR 58331. The High Gain Antenna (HGA) deployment anomaly aboard Galileo is arguably the most significant in-flight problem in this category in terms of current impact on a NASA program. In April 1991, the Galileo spacecraft executed a deployment sequence which was to open the HGA like an umbrella, but it never reached the fully deployed position. It was observed that the two deployment motors operated for 8 minutes instead of 165 seconds, readings for the current drawn by the motors indicated that they stalled after the first minute, and telemetry indicated anomalies in spacecraft spin.

Several attempts were made to force the antenna to deploy:

1. The spacecraft was rotated toward and away from the sun seven times to produce thermal expansion forces at the antenna rib mid-points.

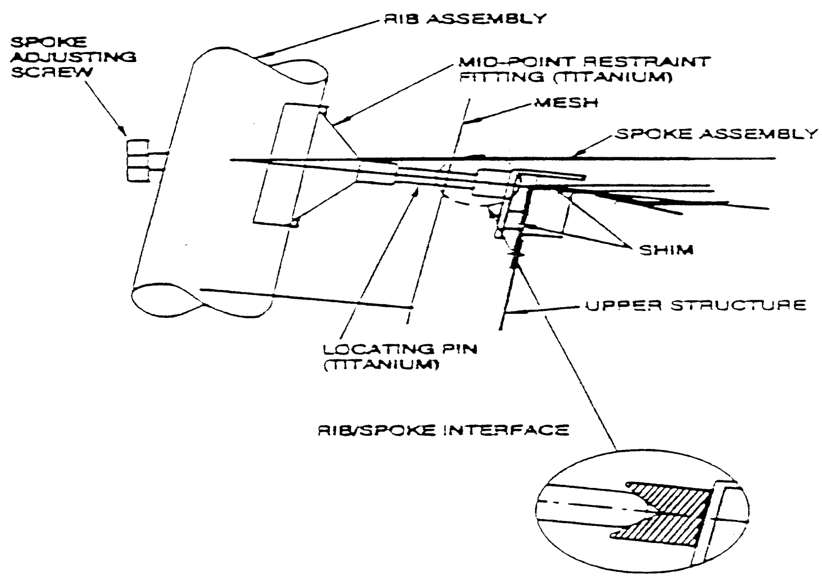
2. The structure of the spacecraft was jolted six times by swinging a Low Gain Antenna (LGA-2).

3. The HGA dual drive motors were pulsed, producing enough torque to pull the ribs loose had they been restrained by the tip fittings.

The failure of these efforts led analysts to believe that several stuck ribs were restrained at the pin and socket fittings, provided at the midpoint of the antenna ribs to prevent flexing during launch. This midpoint restraint features two pins with spherical ends reacting against an 85 lb. preload on the spoke. One pin engages a conical socket and the other a V-groove socket. This V-groove was a JPL innovation; both sockets on the original TDRS design were conical. Figure 2 illustrates the location of the fitting within the rib-spoke interface.

After a two-year investigation at JPL, the failure mechanism was isolated to friction in the midpoint restraint pin/socket interface. Preloading of the ribs when stowed at the factory damaged the V-groove pin ceramic coating, which served as the bonding surface for the dry lubricant. Accumulated stresses from vibration testing, rib preloading, four cross-country trips, and post-launch ignition of the upper stage further dispersed the lubricant film. Due to the resulting friction, some ribs required more force than the drive motors could generate, causing asymmetrical deployment and restraining forces which further reduced the torque available from the drive system. Workarounds using an LGA, new data compression techniques, and the spacecraft's recorder are expected to meet 70 percent of the mission objectives.

Figure 2



Rib/Spoke Interface

Pre-flight ground tests of antenna deployment were successful. The only unresolved pre-flight anomaly (PFR 54090) related to HGA mechanics involved motor power remaining on after HGA deployment during thermal vacuum test. JPL analysts concluded that flight antenna deployment without the actual in-flight relative motion between the pins and sockets passed vacuum test because of the oxides and contaminants on the bare titanium pins. Similarly, ambient ground tests did not reveal this failure mode due to the lower coefficient of friction in air of the titanium pin-to-socket interface. Also, study of the spare antenna revealed that each asymmetrical deployment-stowage cycle during ground test causes enough wear in the ballscrew/ballnut drive assembly to cause a loss in the drive actuator torque available to overcome the rib restraint. Repetitive deployment tests in air would only have worn out the drive system.

The failure analysis for the Galileo High Gain Antenna deployment problem focuses on possible flaws in the design, handling, and testing of a complex mechanism which is required to manipulate a fairly massive hardware item. The launch delay and additional round-trip transport caused by the Challenger disaster may have contributed to the problem. Still, Galileo history illustrates the difficulty of reproducing the spacecraft environment in the ground test of large and complex mechanisms.

Anomaly Cause: Hardware Design

IRU/Gyro Design Defects

Gyros are critical spacecraft assemblies incorporating a level of mechanical complexity similar to the mechanisms discussed above. Most spacecraft carry one or more IRUs, each of which includes the rate measuring electronics plus three or more gyros. Each gyro provides an attitude reference for the spacecraft X-axis (yaw), Y-axis (roll), or Z-axis (pitch), unless it is a two-axis gyro. Unlike those mechanisms which are required to function only once, like antenna/boom deployment drives and instrument cover releases, IRUs have long duty cycles. The JPL solution to reliable navigation on long interplanetary voyages is redundancy via multiple IRUs or gyros.

PFR 41008. After a successful low rate elevation slew of Voyager I, the scan fine pot began to indicate a position change of 1 DN every 12 minutes, until a total indicated position drift of 6 DN had accumulated. In verifying this anomaly, analysts found evidence of similar position creeps during prior elevation slews. The most probable cause of the creep was determined to be cable windup torque pulling the scan platform through the backlash. This IRU anomaly was a scan platform actuator problem, and not an IRU defect. It occurred 2.9 years into the mission.

The problem was resolved by a software workaround. An AACS software patch was added to store the elevation fine pot position and periodically enable the elevation scan actuator drivers. If any creep is registered following a scan, the drivers reposition the scan platform back to the stored fine pot position.

Anomaly Cause: Hardware Design - Functional Application

PFR 41036. The Voyager I "A" gyro was found to show an abnormal drift rate in the pitch axis 2.3 years into the mission. The gyro symptoms were consistent with low gain in the capture loop. In a displacement-type gyro, this electronic loop is employed to convert the offset angle of the gyro rotor to a signal captured by torquer coils surrounding the rotor.

A single part failure mechanism which induced behavior similar to the Voyager anomaly was discovered in tests of the capture electronics. Uncorrected, this problem could cause oscillations in the attitude control system. JPL decided to avoid use of Gyro "A," although periodic conditioning tests to check its performance would permit its use as a reliable backup gyro.

Anomaly Cause: Electronics Part Failure

PFR 52223. During Magellan cruise, the motor current for gyro B-2 was seen to jump from 115 ma to 130 ma, with an accompanying jump in temperature from 44^{0}C. to 46^{0}C. Excessive gyro drift subsequently prevented DSN from locking onto the High Gain Antenna x-band for tape recorder playback. This was followed by further variations in current, temperature, and drift performance which led analysts to attribute the problem to a chattering bearing retainer in the gyro synchronous motor.

Spacecraft attitude control was then transferred to the alternate attitude reference unit (ARU), which has been performing nominally. Gyro B-2 was eventually powered off due to extremely high current levels (>360 ma), and the gyro vendor views it as a failed gyro. Diagnosis of the problem centered on an increase in the gyro motor torque caused by contamination or lack of bearing lubrication.

Anomaly Cause: Possible Quality Control Problem

PFR 52234. Magellan telemetry provided an intermittent indication that two channels on gyro B2 were producing gyro counts at full scale. After gyro power was reset, the B2 outputs were observed to be nominal and consistent with readings from other gyros. Attempts to reproduce this failure mode were unsuccessful, and the cause is unknown. The only corrective action implemented was to reassign the B2 channels to backup use.

Anomaly Cause: Unknown

Comparison of the JPL IRU anomaly experience with that of other agencies in the post-1975 launch time frame shows that the JPL mechanical wearout failure mode is not unique. As noted earlier, the JPL Payload Flight Anomaly Database (PFAD) also contains anomaly data from the Spacecraft Orbital Anomaly Report (SOAR), TIROS/NOAA Orbital Anomaly Report (TOAR), and GOES Anomaly Report (GAR) databases maintained by GSFC, and from the U.S. Air Force Orbital Data Acquisition Program (ODAP) database. The limited set of nomenclatures commonly used to identify IRUs permitted the use of key work searches to establish the scope of non-JPL in-flight gyro problems.

Table 2 summarizes reported GSFC and USAF gyro anomalies aboard platforms launched since 1975. Six out of 125 military spacecraft in the ODAP database (5 percent) experienced IRU failures. For the 38 NASA spacecraft in the GSFC databases, however, 16 spacecraft (42 percent) experienced failures. These included multiple IRUs with an average of two failures per spacecraft. All anomalies studied are apparent failures of an IRU or gyro with the exception of the four IRU anomalies aboard the International Ultraviolet Explorer (IUE) spacecraft, which were characterized as thermistor failures, and the anomalous inertial measurement unit (IMU) logic switching on NOAA 11.[1] Based on the small JPL sample, the average IRU failure occurred about 16 months into the mission for JPL, as compared to 29 months for GSFC. The three IRU failures occurred among six JPL spacecraft which clocked a total of 692 IRU operating months.

III. CONCLUSIONS

The anomalies described in Section II point to the following hardware reliability design issues characteristic of structural and mechanical assemblies:

1. Structures and mechanisms are usually non-redundant. Software patches are useful in remedying command errors but do not correct basic mechanical malfunctions or structural incompatibilities. Operational workaround solutions usually result in some loss of function, excepting minor anomalies.

2. Structures and mechanisms are more likely to result in catastrophic failure; the anomalies studied did not exhibit graceful degradation. Wear out occurs after sustained use-- mechanical parts do not follow the exponential failure distribution common to electronics. Very stringent design standards are required for spacecraft mechanisms intended for one-time use, such as deployment drive trains and latch assemblies for which it may not be feasible to return the hardware to its original state for in-flight repetition of a failed initiation sequence.

[1] A *ailure*, as distinguished from an anomaly, is defined here as an incident in which a unit does not perform all its functions to specification.

Table 2
GSFC and USAF IRU Anomalies*

Spacecraft	Date	Anomaly Description	Mission Impact
GSFC			
COBE (11/89)	11/89	Attitude anomaly due to probable power supply short in RMA-B.	Gyro (-BX?) removed from active control loop. ACS reconfigured.
	01/91	Gyro-AX unstable; stopped 3/20/91. Switched to Gyro-BX backup.	Normal wearout. No effect on attitude control; only on fine aspect solution of science data.
	09/91	Sudden and complete stoppage of Gyro-BX.	Bearing wearout. Switched to backup Gyro-CX. No impact on attitude control.
ERBS (10/84)	02/86	Bearings in IRU-1 yaw gyro failed.	Gyro signal noise increased over 3-12 months until gyro stopped. No impact on attitude control-- experimenters to use workaround procedure. Gyro design lifespan was 2 yrs. Recommendations include fly more gyros, or use more expensive air-bearing gyros.
	07/88	Bearings in IRU-2 roll gyro failed.	
	11/89	Bearings in IRU-1 roll gyro failed.	
	07/90	Bearings in IRU-2 yaw gyro failed.	
HST (04/90)	12/90	Gyro No. 6 failed. Suspected failure in rate sensor electronics.	Standby Gyro No. 2 activated to replace No. 6.
IUE (01/78)	----	TLM readout began to drop slowly on Gyros #1 (7/81), #3 (8/81), #5 (3/82) & #4 (2/84).	Failed thermistor (changes resistance). The temp of the unit was probably unchanged.
	03/82	Gyro No. 1 failed (saturated values)	Causes of gyro failures are unknown. Two gyros remain. Changed ops to 2-gyro fine sun sensor mode. Recommendations include further redundancy such as a second package of gyros.
	07/82	Gyro No. 2 current & temp increased, and gyro stopped.	
	08/85	Rate gyro (IRU) failed. Electronics suspected.	
LANDSAT 2 (01/75)	04/79	Gyro RMP-2 exhibits high current & low rotor speeds due to friction.	Gyro produces erroneous data. Switched to Gyro RMP-1.
LANDSAT 3 (03/78)	05/79	Gyro RMP-2 shows transient high current spikes.	Use Gyro RMP-1 as prime with RMP-2 as a backup if needed.
NIMBUS 7 (10/78)	07/87	Gradual increase in RMP-A ampl. & frequency since 09/86.	Problem appears related to powering of scan mechanism in SMMR instrument.
NOAA 8 (03/83)	06/84	IMU switch inhibit went to YES. All gyro spin motors showed failed.	RXO problems were to be resolved thru RXO design changes.
NOAA 9 (12/84)	04/86	Skew gyro spin motor failure indication.	No recurrence of dropout anomaly since 5/3/86.
NOAA 10 (09/86)	03/87	Skew gyro mean rate output changed over 10 day period, then returned to near normal.	Anomaly observed from Day 063. No attitude perturbations were associated with the event.
NOAA 11 (09/88)	09/89	Roll axis gyro spin motor failed due to short in motor circuit.	Current burned out two flex leads. Considered a random failure.
	07/90	Anomalous IMU logic switching.	No further information.
	06/90	Pitch axis gyro spin motor failure.	No further information.
	09/90	Large yaw update occurred.[1]	Yaw bias filter reset successful.

Spacecraft	Date	Anomaly Description	Mission Impact
NOAA 12 (05/91)	10/92	Erratic skew gyro (IRU) mean rate output.	No further information.
NOAA-B (05/80)	05/80	Update value = 0.209° and increasing due to skew gyro.	Degraded performance due to progressive bias instability.
	07/82	Bias shift in yaw gyro caused yaw updates >0.2 and <1.0 degrees.	Degraded performance due to IRU bias instability.
SMM (02/80)	08/80	IRU Channel C output went to 0: temp loss of attitude reference.	S/C went out of control because channel switch commands were not issued.
	12/80	Partial yaw and TLM signal losses.	Degraded attitude control electronics.
TDRS (04/83)	07/83	Gyro 1/2 failed after extended usage during s/c rescue mission.	Gyro declared unusable.
TIROS N (10/78)	11/79	Yaw update of -9.275°. Error brought sun within FOV of ESA.	No explanation found. Attitude control lost until 01/25/80.
	02/80	Roll gyro (IRU) raw data inconsistent with roll filtered data.	No explanation found. Phenomenon began after 01/25/80 restoration.
	10/80	Pitch gyro (IRU) exhibited progressive bias and output shift.	Pitch gyro degradation. Failure mode unclear.
	12/80	Pitch and roll attitude transients observed.	S/C remained operational on yaw, roll, and skew gyros with degraded response.
	02/81	IMU backup AC p/s failed (reports that primary failed 08/80).	Cause unknown. Causes a questionable IMU status word.
USAF**			
Program A	03/85	Difficulty in controlling s/c due to failure of a part in a gyro's power supply.	Failure: used redundant gyro. Gyros on next flight received extra I&T at the launch site, and some were replaced.
	03/85	Failure of a second gyro.	Ground control forced to employ manual control of thruster firings to orient s/c.
Program B	03/81	Anomalous bias in the gyro (IRU) output due to misalignment of gyro to gyro ass'y, or ass'y to s/c.	Precluded entry to Earth acquisition mode. Mode was attained by ground commands. A ground test procedure to be added.
Program C	12/76	Skew RIG drifting, not useable.	The most probable cause is contamination in fluid gimbal float area due to particles from cracked bender disc. Other possibilities include a bent flux lead, or bubbles in the gimbal float fluid. The s/c continued operations with (1) pitch gyro and (2) earth sensor supplied roll input.
	01/77	Yaw RIG drifting, not useable.	
	03/77	Roll RIG provides erroneous roll rate.	
Program D	11/79	Erratic behavior of the yaw RIG caused earth sensor quadrant loss.	Backup skew gyro commanded to replace yaw gyro (IRU).
	08/80	Primary IMU power supply failed.	Cause unknown. Switched to backup.
	12/80	Failure of pitch RIG: cause unknown.	Switched to yaw gyro compass mode: could mean 1 degree error in attitude performance.

ACS = Attitude Control Subsystem RMP = Rate Measuring Package IRU = Inertial Reference Unit RIG = Rate Integrated Gyro IMU = Inertial Measurement Unit RXO = Redundant Crystal Oscillator FOV = field of view TLM = telemetry

*IRU anomalies caused by software or CPU defects are not included. Some of the identified "gyro" anomalies, such as defective electronics, may be more accurately described as IRU anomalies.
**USAF spacecraft are labeled as Programs A through D because the Air Force has restricted their identification by name.

3. While electronic assemblies make use of standardized packaging processes and interface characteristics, the properties and interactions of structural and mechanical parts are not as easily defined. For a one-of-a-kind flight mechanism, the database for inheritance review cannot match the historical record on an electronic component which has logged millions of operating hours. Life testing of electronic components typically extends for thousands of hours, while it is usually infeasible to undertake repetitive testing of mechanisms.

4. It is very difficult to define a ground test program which can duplicate the exact operating conditions that a structure or mechanism will experience in flight. Environmental variations from the test environment which occur in flight (such as vibration *and* vacuum *and* weightlessness, but occurring only *after* shock occurring *after* an extended period of ground storage) may have a significant mission impact.

Conclusions - Structures/Mechanisms

In 10 of the 13 mechanism actuation anomalies, JPL encountered a problem with the movement of a fairly massive spacecraft structure. The mechanical operation of solar panels, booms, antennas, and instrument covers tend to be mission critical, with no backup capability. In addition, 6 of these 10 involved the release of potential energy stored in these mechanisms. For example, the NIMS cover release system was powered by a preloaded spring. Similarly, at manufacture, each Galileo High Gain Antenna (HGA) spoke assembly was preloaded with 85 lbs. of force exerted against its mid-point restraint. Such single-use deployment mechanisms are required to operate only once during a mission, but with high reliability.

Single-use mechanisms must be robust and fault tolerant where they involve long-term storage of potential energy. Preloading, followed by extended periods under atmospheric and vacuum conditions prior to actuation, can result in:

1. Loss of lubricant and possible corrosion,

2. Mechanically induced damage from handling or shock, vibration, and temperature,

3. Plastic deformation of both the spring and the latch or pivot point,

4. Static friction or cold welding.

There are non-space examples of flight hardware that perform a one-time deployment function with proven reliability. Military ejection seats are highly reliable and utilize rockets to ensure separation from the aircraft. Explosives are used to effect separation of missile stages. Compared to these energy storage devices, a spring has favorable shock, contamination, and safety characteristics. However, the long-term storage of potential energy in compressed materials may cause cold flow, wear, and deterioration during storage, shipping, and flight. Springs create residual stress in the mechanisms used to restrain the stored energy; explosively actuated devices do not. Also, springs require the design of complex release and control mechanisms-- latches, lanyards, and rate limiters. Latent failure modes may be manifested under a combination of environmental conditions not foreseen during ground simulation.

Inheritance reviews must consider all environmental variances. As an example, the Galileo HGA design lacked inheritance from comparable prior missions. The design was based on the Tracking Data Relay Satellite (TDRS) antenna which was designed for earth-orbital missions. A pair of motors was required to overcome the mid-point restraints of 18 antenna spokes preloaded to balanced tension, force the spokes to rotate about their pivots, and to stretch the wire mesh reflector. It is believed that the HGA succumbed to deformation of the contact points on the V-groove pins.[2]

Conclusions - IRUs

Despite their lifespan limitations, the spinning bearing gyros employed by JPL to date are precise and have a long flight history. Gyros must achieve a long service life despite their use of typically high failure rate electro-mechanical parts. Although Section II describes some problems with individual units-- two Voyager I and two Magellan hardware failures-- the backup IRUs were sufficient to support spacecraft navigation in the JPL programs studied. The GSFC IRU failures studied support a conclusion that the limited lifespan of mechanical gyros could present a mission hazard-- of the IRU failures among the 38 NASA spacecraft in the GSFC databases, 18 failures occurred within two years of launch.

Commercial gyro technology offers opportunities for further improvements in mechanical reliability. For example, a hemispherical resonance gyro (HRG), is planned for use aboard Cassini. State-of-the-art gyros may have reliability advantages, but they are as yet unproven in interplanetary spacecraft applications. The presence of a plasma in ring lasers erodes electrodes and optics, and fiber optic lasers may be susceptible to cumulative damage from high power-consuming elements. Hemispheric resonance drivers have not exhibited these problems, but the failure rate of their electronic components remains worthy of reliability engineering review. Presently used for commercial and military navigation on relatively short missions, the major concern with use of the new gyro technologies aboard interplanetary spacecraft is their lack of heritage.

IV. RECOMMENDATIONS

The findings of this study support the need for additional product assurance and related environmental engineering measures in the design of key structural and mechanical assemblies. Table 3 summarizes recommendations for achieving reliable structural and mechanical subsystems on future spacecraft and flight instruments which follow from study of JPL anomalies.

Structural Interference. These anomalies occurred mostly on older spacecraft which were designed without the benefit of sophisticated modeling methods. For structural incompatibilities such as shadowing of solar panels or thruster plume impingement, three-dimensional modeling by computer provides a powerful review tool which was not available during the development of Voyager. Modern simulation techniques allow rotation of virtual spacecraft structures through every attitude anticipated by mission specifications. Any variation from the physical configuration baseline should be carefully modeled for all spacecraft, including the smaller and more standardized spacecraft

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[2]Johnson, Michael R.: The Galileo High Gain Antenna Deployment Anomaly, internal Jet Propulsion Laboratory report, (undated).

Table 3

Product Assurance Program Implications of JPL Spacecraft In-Flight Anomalies

Character-ization	Observations/Lessons Learned	Product Assurance Program Implications
Structural Interference Anomalies	• Viking Orbiter hardware design resulted in IRTM misalignment. • Inadequate structural analysis resulted in Voyager I and II thruster plume impingement, causing propellant losses. • Inadequate structural modeling resulted in unanticipated Magellan ALTA shadowing of a solar panel, causing a minor power loss. • Erroneous Magellan solar panel position calculations caused panel itter and excessive position slippage.	• Review results of three-dimensional computer simulation and structural analysis. • Utilize JPL's integrated modeling environment for successive design iterations on complex systems. • Model and evaluate all variations from the physical configuration baseline.
Mechanical Actuation Anomalies	• Design of the Viking IRTM, Voyager science platform, and Voyager scan platform gear drive trains, and the Voyager PPS analyzer wheel, fostered instrument transit problems. • Actuator and indicator design errors caused anomalous deployment of the Voyager II science boom, Magellan solar panels, Galileo Mag Boom, and Galileo HGA, with severe mission impact. • With an operational change, the thermal design of the Galileo NIMS cover release caused failure to ettison cover. • Uncompensated star scanner misalignment caused Galileo turn errors, threatening damage to instruments and SAS bearings.	• Need for additional environmental testing is not indicated. • Mechanical failure mode analysis and design margin assessment are beneficial in the design and review of complex mechanisms which lack backup. • Following mission ops changes, CogE's and long-tenured JPL experts should revisit design decisions. • Facilitate documentation/transfer of "lessons learned" using design checklists and possibly an expert system. • Minimize institutional barriers to improved communication on design issues, including implementing organizational changes and FRBs.
IRU Anomalies	• No apparent pattern nor trend is evident for the 2 Voyager and 2 Magellan IRU anomalies. Adequate backup was available in all cases. Use of alternatives to spinning bearing gyros is likely for Cassini and subsequent programs.	• Perform failure mechanisms analyses on HRGs and other new gyros to identify principal failure mechanisms to be considered in FMECAs and fault trees.

proposed in the new NASA initiative. Product Assurance should ascertain that changes to mission operations plans are reviewed and modeled for their impact on structural compatibility.

The Project Design Center and the Flight System Testbed are new JPL facilities established to facilitate system-level evaluations of both new and reusable flight hardware. The Project Design Center will establish a capability for integrated modeling of complex systems. It will combine multiple disciplines such as structures, thermal design, and optics in a unified modeling environment permitting rapid design iterations. Although intended primarily for trade-off analysis in costing project alternatives, the Center will offer computer and technical resources which could be applied to concurrent, multi-disciplinary, engineering analysis of environmental effects on structures and mechanisms.

The Flight System Testbed permits JPL to create a virtual spacecraft by connecting components at different stages of development, as well as engineering models. The testbed can simulate other subsystems which interface with the item under test, such as command and data handling. This allows rapid development of hardware prototypes which are flight functional but have not undergone flight qualification. In this simulated environment, preflight-qualified new technology can be "infused" with inherited equipment with greater confidence and reduced cost and risk. Structural incompatibilities which emerge from consecutive design iterations can be identified and solved prior to expensive flight qualification. Participation by Product Assurance in this integrated design process should include:

1. Developing an understanding of the modeling process and capabilities, and

2. Reviewing the results of simulations.

Gyro Defects. Application of state-of-the-art gyro technology to JPL missions offers opportunities for improved hardware lifespan. However, it raises some of the same inheritance issues posed by the Galileo HGA, with the exception that the trend for gyros is in the direction of less mechanical complexity. Given that ring lasers and other new electronic gyros have known reliability problems and lack the flight history of spinning bearing gyros, their application should undergo careful review. For example, a failure mechanisms analysis (FMA) should be performed on hemispherical resonance gyros to identify principal failure mechanisms to be considered in Failure Mode, Effects, and Criticality Analyses (FMECAs) and fault trees for Cassini and subsequent programs.

Mechanical Actuation Problems. The Galileo High Gain Antenna deployment anomaly illustrates the vulnerability of large, complex mechanisms even on a Class A mission when full design review and environmental testing was undertaken. The HGA was a JPL redesign of an antenna developed for the military TDRS system. JPL deleted some TDRS antenna features and added some new ones, but the Galileo HGA deployment mechanism remained very similar to TDRS. Ten TDRS satellites have been launched, and their antennas were all successfully deployed.

Selection of an earth orbital antenna design, even though proven in that application, was not fully consistent with the Galileo mission. The deep space mission subjected the antenna to environmental conditions not encountered by TDRS in Earth orbit, and Galileo's VEEGA mission profile extended the duration of those conditions. Added to this was an unanticipated 3½ year launch delay and extra ground handling resulting from the Challenger disaster. Ambient and vacuum tests failed to reveal damage believed to have occurred when the antenna was first preloaded following manufacture. Additional testing of the deployment mechanism would have worn out the deployment drive system.

Given these circumstances, it is not clear that traditional product assurance measures, such as additional ground test, would have revealed the vulnerability. Latent design flaws in complex mechanisms may not be manifested until some wear and tear has taken place. The chance of mechanism failure from such flaws increases with mechanical complexity. In the case of the Galileo HGA ground test, the oxides and contaminants on the bare titanium pins helped to mask the effects of damage to the ceramic pin coating. In a mechanism like a deployment drive which has a design requirement to operate only once, there is little opportunity to observe degraded performance over time.

For such critical mechanisms, effective product assurance measures include those which enhance understanding of potential failure modes at an early stage of design. Early use of some of the new mechanical design and analysis tools may support design changes to provide greater mechanical redundancy, use of a simpler mechanism, or elimination of a "single-use" mechanism. Use of such additional design analysis techniques is recommended for critical mechanisms which have not previously been flown on extended missions. For inherited hardware, design margin assessments should establish that design margins are adequate to accommodate wear and any potential flaws. Enhanced peer review utilizing a checklist of known failure mechanisms is also recommended.

A problem with development of interplanetary flight hardware is that mechanical design analysis is generally not as thorough as that for electronics. NASA has no mechanical parts equivalent to an Electronic Parts Group, and a Standard Parts List of approved mechanical parts is not usually practical. This problem is compounded by the lack of repetitive testing on a scale comparable to the thousands of hours electronic components are tested. JPL utilizes non-electronic fault tree analysis (FTA) to study the specific failure modes that lead to a hypothetical hardware failure. For example, FTA assumes a stuck motor and then evaluates the various motor components for failure modes which could cause such a jam, as shown in Figure 3. This methodology may overlook specific failure mechanisms in mechanical devices. Use of failure mechanisms analysis (FMA) would improve fault trees by highlighting the underlying "physics of failure" issues that cause the failure modes in the fault tree or FMEA.

These failure mechanism checklists should be periodically updated based on ground test and in-flight failures so that the fault tree or FMECA analyst is continually reminded to consider them in the analysis. This would then emphasize the effect that a specific mission profile might have on the particular failure mechanism due to long-term storage, extended vacuum conditions, etc. Figure 3 illustrates how this failure mechanisms checklist might be used.

The Flight System Testbed will incorporate an evolving body of knowledge consolidating new and inherited technology. This facility can interface instruments, sensors, and subsystems through flight computers, a ground data system interface, and a spacecraft dynamic simulator. As successive design iterations are integrated into the virtual spacecraft and tested for system-level functionality and interface compatibility, the cost impact of mechanism design margins can be assessed. Allowing problems to be identified at an early stage of development, the testbed will facilitate inheritance of hardware designs from project to project. For the Mars Environmental Survey (MESUR) Pathfinder, current plans call for the testbed to be used to model or simulate spacecraft interfaces that might be troublesome. The capability of the testbed to simulate mechanical interfaces, as well as electronic interfaces, should be explored by JPL.

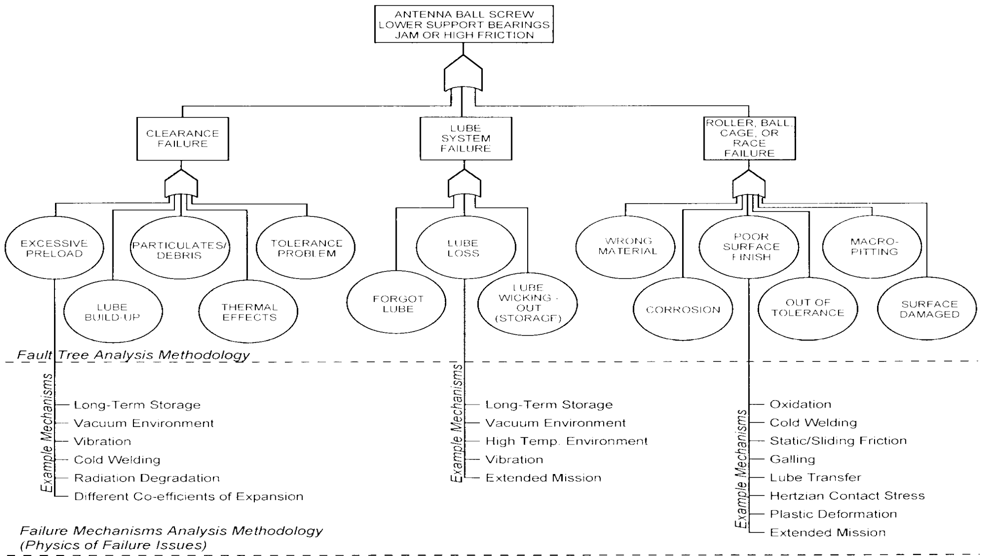

Figure 3
Example of Fault Tree Analysis[3] Augmented By FMA

These engineering advancements must be coupled with improved two-way communications between hardware designers and mission operations-cognizant personnel. For example, the modified TDRS antenna design might have proven adequate for the Galileo mission as originally planned. However, the design should have been subjected to intensive review after the decision to delay launch 3½ years, and after the subsequent decision to take the VEEGA route to Jupiter. When such major changes are made to plans for spacecraft storage and handling or to the mission profile, an intensive peer review panel should be convened to review the impact of the changes on essential subsystems. Modifications are frequently not given the same level of scrutiny as the original design. The panel should call upon the expertise of:

1. **Project Development Team**. This review of essential subsystems must extend down to the component level. The component engineer's cognizance typically ends with the receipt of a piece part which meets specifications which were based on the anticipated environment. The effect of changes to the mission environment may not be clear to the design engineer, who may have accepted the piece part without fully understanding the limitations on its application.[4] Seemingly minor operational changes have had significant mission impacts. For example, the decision by Mission Operations to leave the NIMS shield heater activated during cover deployment was implemented without consulting the hardware designers. Such decisions should be made with the concurrence of the appropriate hardware engineering personnel.

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[3] Johnson, S.A.: Galileo S/X-Band Antenna Fault Tree Matrix, internal Jet Propulsion Laboratory document, June 22, 1981, p. 14.

[4] Oberhettinger, D.: Investigation of Thermal Sensor Failures Aboard Unmanned Spacecraft, Jet Propulsion Laboratory Document JPL D-11377, April 1994, p. 12.

2. **Long-Tenured JPL Experts**. A major JPL resource is personnel who may not have participated in design of the subject spacecraft, but have been involved in spacecraft planning and design since JPL's early years. It is not uncommon at JPL for the Deputy Director of the Laboratory to personally review a design for a familiar subsystem, but this resource is spottily used. For example, JPL is presently investigating cold welding in vacuum as a possible explanation for the jamming of the Galileo HGA pin/socket fitting (PFR 58331). There are senior JPL engineers still on staff who are familiar with spacecraft design measures instituted in the early '60s to eliminate such point contacts and prevent cold welding. Improved procedures to access this institutional memory bank should be established and used systematically.

   Ideally, JPL should seek to "bank" these assets. To facilitate transfer of "lessons learned" and to retain the JPL knowledge base against employee retirements and turnover, priority should be given to development of design checklists, engineering best practices manuals, and possibly an expert system to support spacecraft design. This would be particularly applicable to mechanical design; electronic circuit designers have access to a variety of commercially available analysis tools. This resource would preserve and augment JPL's areas of expertise within the space exploration community.

With smaller, short development time missions, it is possible that the hardware designer and the mission control operator may be the same person. This arrangement would aid in identifying the impacts of mission changes.

Institutional barriers to the improved communications necessary to isolate potential mechanical design problems may exist within the JPL organizational structure. Hardware reliability and environmental design review is the province of JPL Reliability Engineering (Section 505). The JPL D-1489 product assurance standard specifies non-electronic fault tree analysis for all Class A and B flight equipment. However, because Section 505 staff resources are focused primarily on analog and digital circuit analysis, this responsibility typically falls upon Mechanical Systems Engineering (Division 350) within the Office of Technical Divisions. In many cases, mechanical design issues need to be resolved at the Systems Engineering level, but this organization is not often involved throughout the design process. During hardware development and test, every major JPL program should convene a Problem/Failure Review Board which draws membership from Systems Engineering, Product Assurance, Safety Engineering, and Configuration Management, with the cognizant design engineers in support. Providing concurrent review of problems and collective decisionmaking on solutions, this body proved effective on the JPL All Source Analysis System (ASAS) ground hardware program in connecting the various JPL organizations. Improvement of the Reliability Engineering Section's mechanical design review capabilities, including staff resources, should also be considered.

The evolving JPL integrated design and modeling environment provides a venue for implementing these recommendations for structural modeling, expert systems, concurrent review of problems, design review updates following mission changes, and improved communications to remove institutional barriers. The Project Design Center will support concurrent engineering by bringing together all design specialists at project inception, and the Flight System Testbed will reduce the cost of exploring design alternatives. The computer resources in these facilities can accommodate tools for capturing mission and systems design knowledge. These resources offer opportunities for improved Systems Engineering insight into system-level functionality and interface compatibility. By revealing system-level design flaws prior to expensive test-and-fix cycles, Reliability Engineering oversight can assist in meeting cost and schedule requirements.

These mechanical design issues will remain relevant to future spacecraft programs. They are applicable to the family of miniaturized spacecraft planned by NASA, which feature reduced backup hardware. Envisioned as low cost and short development time, these programs are not likely to receive the reliability analysis resources formerly devoted to the design of large missions like Cassini. With less hardware redundancy in the small spacecraft, they will also be more dependent on software to fix in-flight problems. However, the mechanical problems studied here were not amenable to direct software solutions. Although workarounds were sometimes effective in reducing the mission impact, the new small spacecraft are expected to incorporate greater functional autonomy from ground controllers. Such autonomy would greatly reduce mission operation and other life cycle costs. However, spacecraft autonomy increases the mission risk from unanticipated structural/mechanical flaws uncorrectable by on-board software, and independent decisionmaking will reduce the ability of ground controllers to implement new corrective measures to counteract unanticipated problems.

Risk management in the next generation of NASA spacecraft will require product assurance programs that detect failure mechanisms on the ground and anticipate necessary corrective actions so that they can be built into autonomous systems. This will require improved product assurance efficiency which may be attained by concentrating on historically important failure mechanisms and their effects and by integrating the product assurance function with the design function through the concurrent engineering process.

ENDNOTE

1 [From page 18, row 4] A number of the IRU anomaly reports described a symptom in which telemetry indicated a large or increasing "update value." In Inertial mode, the scan platform attitude estimate needed for science pointing is determined from gyro data. Several times per revolution, the SEQID procedure identifies a star. The star data is used to update the gyro-based platform attitude estimate. An update value, indicating a discrepancy between the gyro-based and the star-based attitude estimates, is interpreted as a position error. An increasing update value may be consistent with a failure mode like bearing wearout.